Vector-like quarks t' and partners

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Outline

1. Motivations and Current Status
2. Couplings and constraints
3. Signatures at LHC

Outline

What are vector-like fermions?

and where do they appear?

The left-handed and right-handed chiralities of a vector-like fermion ψ transform in the same way under the SM gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$

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Charged current Lagrangian

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- SM chiral quarks: ONLY left-handed charged currents

$$J^{\mu+} = J_L^{\mu+} + J_R^{\mu+} \quad \text{with} \quad \begin{cases} J_L^{\mu+} = \bar{u}_L \gamma^\mu d_L = \bar{u} \gamma^\mu (1-\gamma^5) d = V - A \\ J_R^{\mu+} = 0 \end{cases}$$

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$$J^{\mu +} = J^{\mu +}_L + J^{\mu +}_R \qquad \text{with} \qquad \begin{cases} J^{\mu +}_L = \bar{u}_L \gamma^\mu d_L = \bar{u} \gamma^\mu (1 - \gamma^5) d = V - A \\ J^{\mu +}_R = 0 \end{cases}$$

- vector-like quarks: BOTH left-handed and right-handed charged currents

$$J^{\mu +} = J^{\mu +}_L + J^{\mu +}_R = \bar{u}_L \gamma^\mu d_L + \bar{u}_R \gamma^\mu d_R = \bar{u} \gamma^\mu d = V$$

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Vector-like quarks in many models of New Physics

- Warped or universal **extra-dimensions**
  KK excitations of bulk fields
- **Composite Higgs** models
  VLQ appear as excited resonances of the bounded states which form SM particles
- **Little Higgs** models
  partners of SM fermions in larger group representations which ensure the cancellation of divergent loops
- **Gauged flavour group** with low scale gauge flavour bosons
  required to cancel anomalies in the gauged flavour symmetry
- Non-minimal **SUSY extensions**
  VLQs increase corrections to Higgs mass without affecting EWPT

SM and a vector-like quark

$\mathcal{L}_M = -M\bar{\psi}\psi$ Gauge invariant mass term without the Higgs

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Charged currents both in the left and right sector

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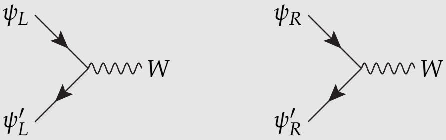
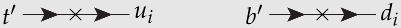


They can mix with SM quarks

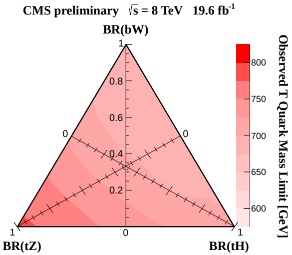


Dangerous FCNCs $\longrightarrow$ strong bounds on mixing parameters
BUT
Many open channels for **production** and **decay** of heavy fermions

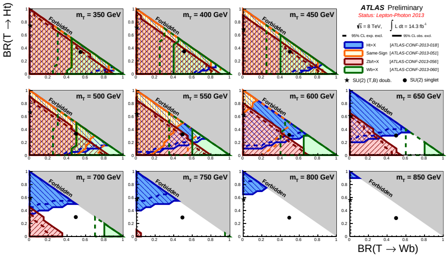
Rich phenomenology to explore at LHC

Searches at the LHC

CMS (t')



ATLAS (t')

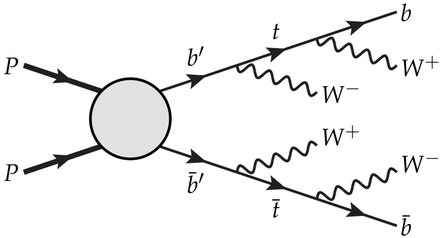


Bounds from pair production between 600 GeV and 800 GeV

depending on the decay channel

Common assumption: mixing with third generation only

Example: b' pair production



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CC: $b' \to tW$

Searches in the
same-sign dilepton channel
(possibly with b-tagging)

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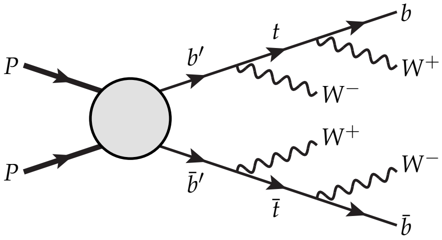

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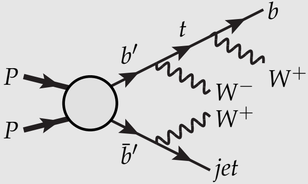
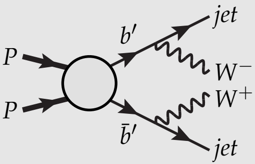
If the b' decays both into Wt and Wq





There can be less events in the same-sign dilepton channel!

Representations and lagrangian terms

Assumption: vector-like quarks couple with SM quarks through Yukawa interactions

Representations and lagrangian terms

Assumption: vector-like quarks couple with SM quarks through Yukawa interactions

	SM	Singlets		Doublets			Triplets	
	$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$	(U)	(D)	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
$SU(2)_L$	2 and 1	1		2			3	
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	2/3	-1/3	7/6	1/6	-5/6	2/3	-1/3
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c U_R$ $-\lambda_d^i \bar{q}_L^i H D_R$		$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$			$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$	

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$\mathcal{L}_m$		$-M\bar{\psi}\psi$ (gauge invariant since vector-like)						
Free parameters		4 $M + 3 \times \lambda^i$		4 or 7 $M + 3\lambda_u^i + 3\lambda_d^i$			4 $M + 3 \times \lambda^i$	

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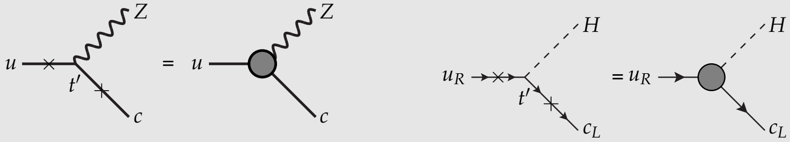
Flavour changing neutral currents in the SM



and flavour conserving neutral currents receive a contribution

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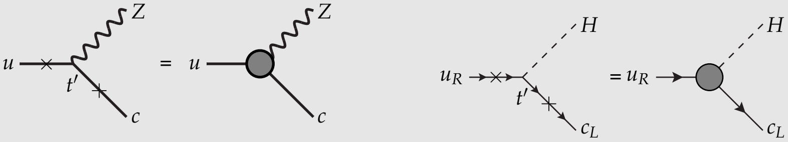
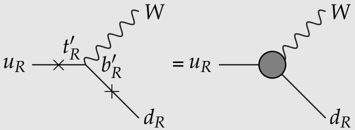


and flavour conserving neutral currents receive a contribution

Charged currents between right-handed SM quarks



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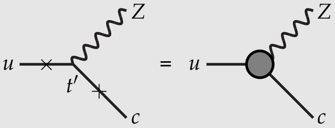
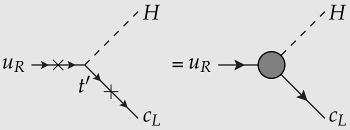
Couplings

Major consequences

Flavour changing neutral currents in the SM





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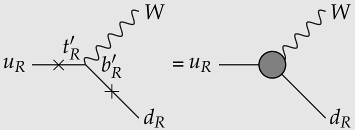
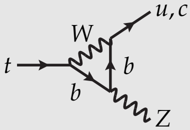


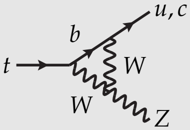
and charged currents between left-handed SM quarks receive a contribution

All proportional to combinations of mixing parameters

FCNC constraints

Rare top decays

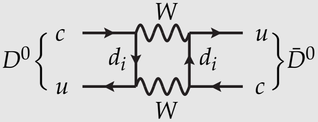


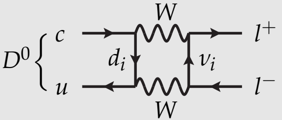


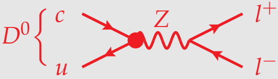
$BR(t \to Zq) = \mathcal{O}(10^{-14})$
SM prediction

$BR(t \to Zq) < 0.24\%$
measured at CMS @ 5 fb^{-1}

Meson mixing and decay

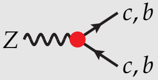






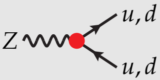
Flavour conserving NC constraints

$Zc\bar{c}$ and $Zb\bar{b}$ couplings



- Direct coupling measurements: $g^q_{ZL,ZR} = (g^q_{ZL,ZR})^{SM}(1 + \delta g^q_{ZL,ZR})$
- Asymmetry parameters: $A_q = \frac{(g^q_{ZL})^2 - (g^q_{ZR})^2}{(g^q_{ZL})^2 + (g^q_{ZR})^2} = A_q^{SM}(1 + \delta A_q)$
- Decay ratios: $R_q = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to hadrons)} = R_q^{SM}(1 + \delta R_q)$

Atomic parity violation



Weak charge of the nucleus

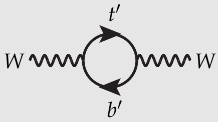
$$Q_W = \frac{2c_W}{g}\left[(2Z+N)(g^u_{ZL} + g^u_{ZR}) + (Z+2N)(g^d_{ZL} + g^d_{ZR})\right] = Q_W^{SM} + \delta Q_W^{VL}$$

Most precise test in Cesium ^{133}Cs:

$$Q_W(^{133}\text{Cs})|_{exp} = -73.20 \pm 0.35 \qquad Q_W(^{133}\text{Cs})|_{SM} = -73.15 \pm 0.02$$

Constraints from EWPT and CKM

EW precision tests



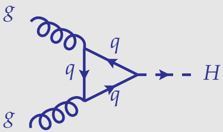
Contributions of new fermions
to S,T,U parameters

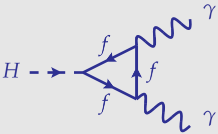
CKM measurements

- Modifications to CKM relevant for singlets and triplets because mixing in the left sector is NOT suppressed
- The CKM matrix is not unitary anymore
- If BOTH t' and b' are present, a CKM for the right sector emerges

Higgs coupling with gluons/photons

Production and decay of Higgs at the LHC





New physics contributions mostly affect loops of heavy quarks t and q':

$$\kappa_{gg} = \kappa_{\gamma\gamma} = \frac{v}{m_t} g_{ht\bar{t}} + \frac{v}{m_{q'}} g_{hq'\bar{q}'} - 1$$

The couplings of t and q' to the higgs boson are:

$$g_{ht\bar{t}} = \frac{m_t}{v} + \delta g_{ht\bar{t}} \qquad g_{hq'\bar{q}'} = \frac{m_{q'}}{v} + \delta g_{hq'\bar{q}'}$$

In the SM: $\kappa_{gg} = \kappa_{\gamma\gamma} = 0$

The contribution of just one VL quark to the loops turns out to be negligibly small

Result confirmed by studies at NNLO

Outline

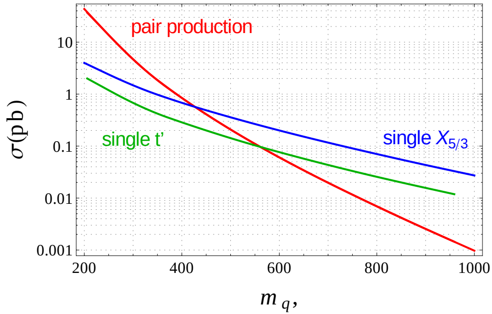
Production channels

Vector-like quarks can be produced
in the same way as SM quarks **plus** FCNCs channels

- **Pair production**, dominated by QCD and sentitive to the q' mass independently of the representation the q' belongs to
- **Single production**, only EW contributions and sensitive to both the q' mass and its mixing parameters

Production channels

Pair vs single production, example with non-SM doublet $(X_{5/3}\ t')$

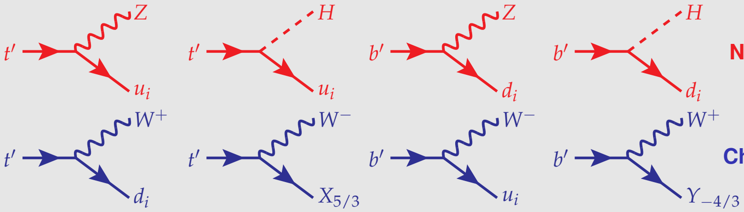


pair production depends only on the mass of the new particle and **decreases faster** than single production due to different **PDF scaling**

current **bounds from LHC** are around the region where (model dependent) **single production dominates**

Decays

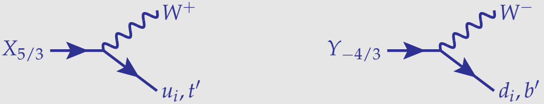
SM partners



Neutral currents

Charged currents

Exotics

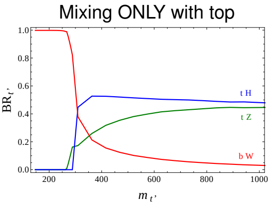


Only Charged currents

Not all decays may be kinematically allowed

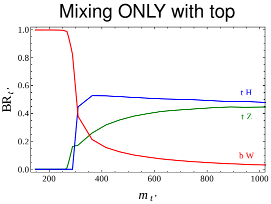
it depends on **representations** and **mass differences**

Decays of t'



Equivalence theorem at large masses: $BR(qH) \simeq BR(qZ)$
Decays are in different channels (BR=100% hypothesis now relaxed in exp searches)

Decays of t'



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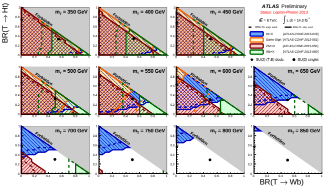
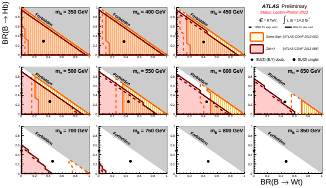
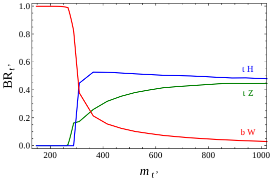
Still, current bounds assume mixing with third generation only!





Decays of t'

Mixing ONLY with top



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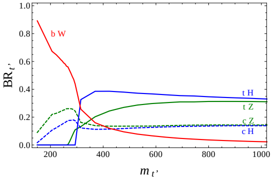
Mixing with top and charm



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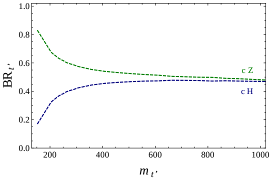

Decay to lighter generations can be sizable
even if Yukawas are small!

Single Production

based on arXiv:1305.4172, accepted by Nucl.Phys.B

From couplings to BRs

Charged current of T (t')

$$\mathcal{L} \supset \kappa_W V_{L/R}^{4i} \frac{g}{\sqrt{2}} \, [\bar{T}_{L/R} W_\mu^+ \gamma^\mu d_{L/R}^i]$$

From couplings to BRs

Charged current of T (t')

$$\mathcal{L} \supset \kappa_W V^{4i}_{L/R} \frac{g}{\sqrt{2}} \, [\bar{T}_{L/R} W^+_\mu \gamma^\mu d^i_{L/R}]$$

Partial Width

$$\Gamma(T \to W d_i) = \kappa_W^2 |V^{4i}_{L/R}|^2 \frac{M^3 g^2}{64 \pi m_W^2} \Gamma^0_W(M, m_W, m_{d_i} = 0)$$

Assumption: massless SM quarks, corrections for decays into top (see 1305.4172)

From couplings to BRs

Charged current of T (t')

$$\mathcal{L} \supset \kappa_W V^{4i}_{L/R} \frac{g}{\sqrt{2}} \left[\bar{T}_{L/R} W^+_\mu \gamma^\mu d^i_{L/R}\right]$$

Partial Width

$$\Gamma(T \to W d_i) = \kappa_W^2 |V^{4i}_{L/R}|^2 \frac{M^3 g^2}{64\pi m_W^2} \Gamma^0_W(M, m_W, m_{d_i} = 0)$$

Assumption: massless SM quarks, corrections for decays into top (see 1305.4172)

Branching Ratio

$$BR(T \to W d_i) = \frac{|V^{4i}_{L/R}|^2}{\sum_{j=1}^3 |V^{4j}_{L/R}|^2} \cdot \frac{\kappa_W^2 \Gamma^0_W}{\sum_{V'=W,Z,H} \kappa^2_{V'} \Gamma^0_{V'}} \equiv \zeta_i \xi_W$$

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Re-expressing the Lagrangian

$$\mathcal{L} \supset \kappa_T \sqrt{\frac{\zeta_i \xi_W}{\Gamma^0_W}} \frac{g}{\sqrt{2}} [\bar{T}_{L/R} W^+_\mu \gamma^\mu d^i_{L/R}] \quad \text{with} \quad \kappa_T = \sqrt{\sum_{i=1}^3 |V^{4i}_{L/R}|^2 \sqrt{\sum_V \kappa_V^2 \Gamma^0_V}}$$

The complete Lagrangian

$$
\begin{aligned}
\mathcal{L} \;=\;& \kappa_T \left\{ \sqrt{\frac{\zeta_i \xi_W^T}{\Gamma_W^0}} \frac{g}{\sqrt{2}} \, [\bar{T}_L W_\mu^+ \gamma^\mu d_L^i] + \sqrt{\frac{\zeta_i \xi_Z^T}{\Gamma_Z^0}} \frac{g}{2c_W} \, [\bar{T}_L Z_\mu \gamma^\mu u_L^i] - \sqrt{\frac{\zeta_i \xi_H^T}{\Gamma_H^0}} \frac{M}{v} \, [\bar{T}_R H u_L^i] - \sqrt{\frac{\zeta_3 \xi_H^T}{\Gamma_H^0}} \frac{m_t}{v} \, [\bar{T}_L H t_R] \right\} \\
&+ \kappa_B \left\{ \sqrt{\frac{\zeta_i \xi_W^B}{\Gamma_W^0}} \frac{g}{\sqrt{2}} \, [\bar{B}_L W_\mu^- \gamma^\mu u_L^i] + \sqrt{\frac{\zeta_i \xi_Z^B}{\Gamma_Z^0}} \frac{g}{2c_W} \, [\bar{B}_L Z_\mu \gamma^\mu d_L^i] - \sqrt{\frac{\zeta_i \xi_H^B}{\Gamma_H^0}} \frac{M}{v} \, [\bar{B}_R H d_L^i] \right\} \\
&+ \kappa_X \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} \, [\bar{X}_L W_\mu^+ \gamma^\mu u_L^i] \right\} \\
&+ \kappa_Y \left\{ \sqrt{\frac{\zeta_i}{\Gamma_W^0}} \frac{g}{\sqrt{2}} \, [\bar{Y}_L W_\mu^- \gamma^\mu d_L^i] \right\} \\
&+ h.c.
\end{aligned}
$$

Model implemented and validated in Feynrules: http://feynrules.irmp.ucl.ac.be/wiki/VLQ

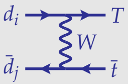
$$\sum_{i=1}^{3} \zeta_i = 1 \qquad \sum_{V=W,Z,H} \xi_V = 1$$

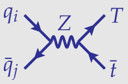
- T and B: NC+CC, 4 parameters each ($\zeta_{1,2}$ and $\xi_{W,Z}$)
- X and Y: only CC, 2 parameters each ($\zeta_{1,2}$)

Cross sections (example with T)

In association with top

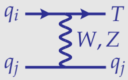
$$\sigma(T\bar{t}) = \kappa_T^2 \left(\xi_Z \zeta_3 \, \bar{\sigma}^{T\bar{t}}_{Z3} + \xi_W \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}^{T\bar{t}}_{Wi} \right)$$

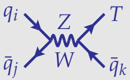




In association with light quark

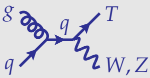
$$\sigma(Tj) = \kappa_T^2 \left(\xi_W \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}^{Tjet}_{Wi} + \xi_Z \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}^{Tjet}_{Zi} \right)$$

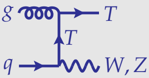


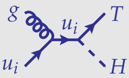


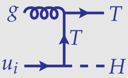
In association with gauge or Higgs boson

$$\sigma(T\{W,Z,H\}) = \kappa_T^2 \left(\xi_W \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}^{TW}_{i} + \xi_Z \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}^{TZ}_{i} + \xi_H \sum_{i=1}^{3} \zeta_i \, \bar{\sigma}^{TH}_{i} \right)$$









The $\bar{\sigma}$ are model-independent coefficients: the model-dependency is factorised!

Cross sections

Coefficients (in fb) for T and $\bar{T}$ with mass 600 GeV

	with top		with light quark		with gauge or Higgs		
	$\bar{\sigma}_{Zi}^{T\bar{t}+\bar{T}t}$	$\bar{\sigma}_{Wi}^{T\bar{t}+\bar{T}t}$	$\bar{\sigma}_{Zi}^{Tj+\bar{T}j}$	$\bar{\sigma}_{Wi}^{Tj+\bar{T}j}$	$\bar{\sigma}_{i}^{TZ+\bar{T}Z}$	$\bar{\sigma}_{i}^{TH+\bar{T}H}$	$\bar{\sigma}_{i}^{TW+\bar{T}W}$
$\zeta_1 = 1$	-	1690	69200	51500	5480	3610	2430
$\zeta_2 = 1$	-	247	5380	10700	202	133	374
$\zeta_3 = 1$	12.6	78.2	-	4230	-	-	122

The cross section for pair production is 170 fb

Cross sections

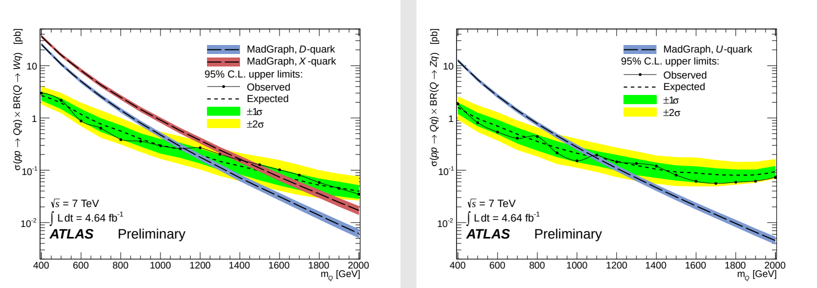
Embed the model-dependency into a consistent framework

		Benchmark 1 $\kappa = 0.02$ $\zeta_1 = \zeta_2 = 1/3$	Benchmark 2 $\kappa = 0.07$ $\zeta_1 = 1$	Benchmark 3 $\kappa = 0.2$ $\zeta_2 = 1$	Benchmark 4 $\kappa = 0.3$ $\zeta_3 = 1$	Benchmark 5 $\kappa = 0.1$ $\zeta_1 = \zeta_3 = 1/2$	Benchmark 6 $\kappa = 0.3$ $\zeta_2 = \zeta_3 = 1/2$
$(1, 2/3)$	T	15	464	564	399	495	834
$(1, -1/3)$	B	14	455	457	167	-	-
$(2, 1/6)$	T	5.6	191	114	0.6	195	128
$\lambda_d = 0$	B	10	351	267	1.1	358	301
$(2, 1/6)$	T	9.5	272	451	398	-	-
$\lambda_u = 0$	B	3.7	103	190	166	-	-
$(2, 1/6)$	T	15	464	564	399	-	-
$\lambda_d = \lambda_u$	B	14	455	457	167	-	-
$(2, 7/6)$	X	15	528	272	1.2	538	307
	T	5.6	191	114	0.6	195	128
$(2, -5/6)$	B	3.7	103	190	166	-	-
	Y	7.6	205	443	388	-	-
$(3, 2/3)$	X	30.5	1055	545	2.4	-	-
	T	15	464	564	399	-	-
	B	7.4	207	380	332	-	-
$(3, -1/3)$	T	5.6	191	114	0.6	-	-
	B	7.1	227	228	84	-	-
	Y	7.6	205	443	388	-	-

Flavour bounds are necessary to get the inclusive cross sections

Flavour vs direct search

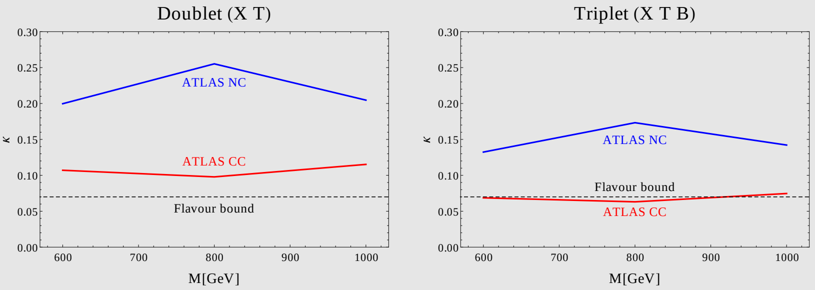
ATLAS search in the CC and NC channels



Assumptions: mixing only with 1st generation and coupling strength $\kappa = \frac{v}{M_{VL}}$

Flavour vs direct search

Comparison with flavour bounds



Assumptions: mixing only with 1st generation and coupling strength saturating flavour bounds

Flavour bounds are competitive with current direct searches

Conclusions and Outlook

- After Higgs discovery, **Vector-like quarks** are a very promising playground for searches of new physics
- Fairly **rich phenomenology at the LHC** and many possibile channels to explore
  - → Signatures of single and pair production of VL quarks are **accessible at current CM energy and luminosity** and have been explored to some extent
  - → Current bounds on masses around **600-800 GeV**, but searches are not fully optimized for **general scenarios**.
- **Model-independent studies** can be performed for **pair** and **single production**, and also to analyse scenarios with **multiple vector-like quarks** (work in progress, results very soon!)